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Thermostrictive Recording on Permalloy Films

Abstract: Where the magnetostrictive coefficient is of the order of 10^{-4} or greater, recording may be accomplished on uniaxial Permalloy films by the application of a local stress in coincidence with a biasing field. Here, the stress is introduced into the film as a result of a temperature gradient produced by an incident laser or electron beam.

The mechanism of recording is studied and a model developed in agreement with the mechanism. Several modes of recording are discussed, with the advantages and disadvantages of each. Extrapolating the model to a large capacity memory of 10^7 bits per square inch with 8 micron diameter spots on a Permalloy film having a magnetostrictive coefficient of 10^{-6} , a 20°C temperature rise will be experienced with 2×10^{-10} joules of energy in the beam. The beam power required is 10^{-3} watts at 10% efficiency and a one megacycle information rate.

Introduction

The search for extremely large capacity memories ($>10^8$ bits) has encouraged investigators to explore new mechanisms for recording. There has been a tendency by these investigators to lean toward a beam-operated memory because the facility and speed of input and output remain high when a large number of storage positions must be addressed. The thermoplastic recording¹ scheme by W. E. Glenn is such a device. Other schemes rely upon a compensation temperature with a change in state; e.g., Dillon et al.² have proposed and operated a limited-population memory using a ferrimagnetic garnet and driven by a laser beam. We will describe here another scheme in which recording is effected on uniaxial Permalloy films by the application of a localized stress introduced by either a laser or an electron beam.

Theoretical considerations

The effect of stress applied to uniaxial films has been treated by many investigators. However, in the main, these investigations examine the characteristics of the film and do not specifically consider the utility of such a mechanism for a memory.

One paper of particular note, from which we draw heavily in constructing a model for the thermostrictive recording, is that by Mitchell³ and his coworkers. They derive the expression

$$\sigma = \frac{M_s H_k}{3\lambda_s} \frac{\sin 2\theta_0}{\sin 2(\beta - \theta_0)}, \quad (1)$$

for the case of an externally applied stress σ , at an angle β with respect to the easy axis in the absence of an applied field. The symbol λ_s represents the saturation magneto-

striction and the angle θ_0 represents the rotation of the anisotropy under the applied stress where the magnetostriction λ_s is assumed to be isotropic.

We are primarily interested in that stress which is the consequence of a localized temperature gradient introduced in the film by a beam. The energy distribution of the beam, and consequently the temperature distribution of the irradiated spot, may be assumed Gaussian when the energy is delivered in a burst sufficiently short compared to the diffusion of heat through the metallic film. The temperature distribution may be approximated as

$$\Delta T(r) = \Delta T_0 \left(1 - \frac{r^2}{b^2}\right), \quad (2)$$

where ΔT_0 is the maximum temperature rise within the beam spot of diameter b .

The total energy required to raise the temperature of a given spot according to the distribution of Eq. (2) is

$$E = 2\pi t C \rho \int_0^b r \Delta T(r) dr,$$

and

$$E = (\pi/2) t C \rho b^2 \Delta T_0, \quad (3)$$

where t is the film thickness, ρ the mass density and C the specific heat. Wang⁴ calculates the stress on a thin circular disk resulting from the temperature distribution of Eq. (2) as

$$\sigma_r = -\frac{1}{4}\alpha Y \Delta T_0 [1 - (r^2/b^2)], \quad (4)$$

$$\sigma_\theta = -\frac{1}{4}\alpha Y \Delta T_0 [1 - (3r^2/b^2)],$$

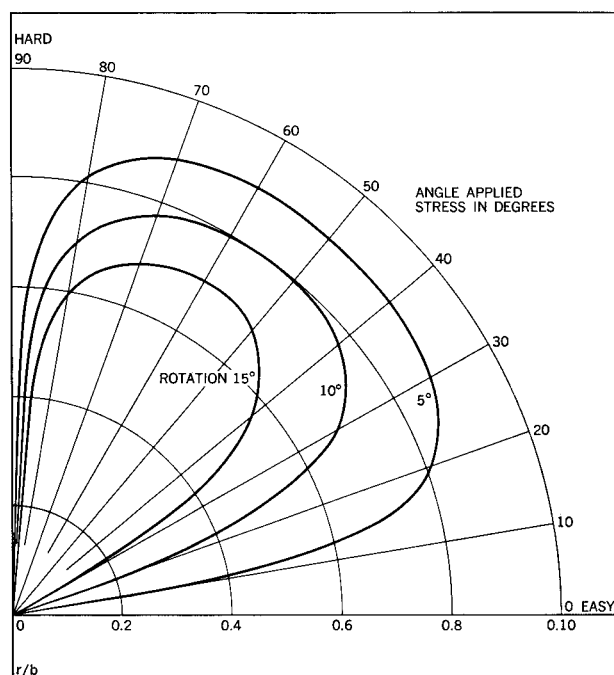


Figure 1 Radial stress.

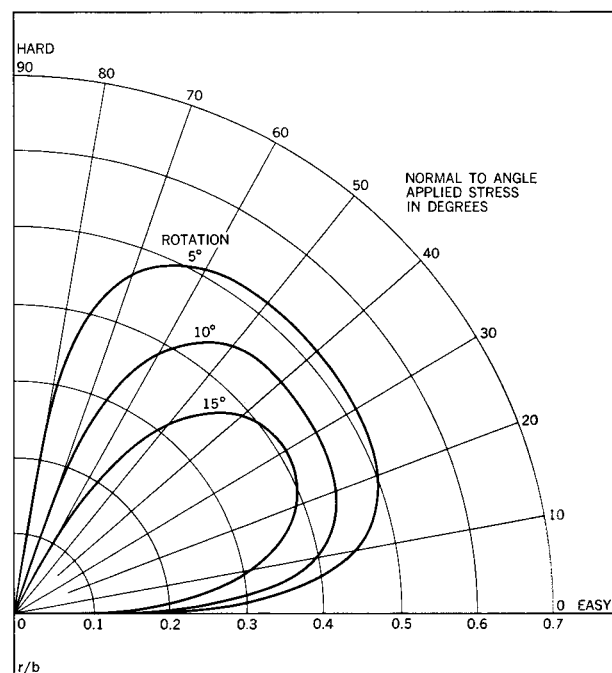


Figure 2 Tangential stress.

where α is the coefficient of linear expansion, and Y stands for Young's modulus. To facilitate handling of the equations we normalize Eq. (1) against

$$\sigma_0 = \frac{M_s H_k}{3\lambda_a}, \quad (5)$$

which is the stress required to effect a rotation when applied along the hard direction. Equation 4 is normalized against

$$\sigma' = \frac{1}{4}\alpha Y \Delta T_0 \quad (6)$$

for convenience in plotting. That is, when the stress is applied in the hard direction, the energy of the beam is limited to just that required to cause rotation at the origin.

Equating the reduced Eqs. (1) and (4), we arrive at the first quadrant plots for the radial stress (Fig. 1) and for the tangential stress (Fig. 2). The reduced stress values are obtained from Table 1.

In plotting the tangential stress, the region in tension (the outer edge) is ignored. As the stress increases beyond unity, the position of unity stress moves radially outward along the asymptotes. It is seen from the plots as well as from the equations that no value of radial applied stress along the easy axis will cause a rotation. While a rotation at points along the easy axis will result from the tangential stress component, its effect is limited to lie within 60 per cent of the beam radius. The effect of the radial stress will, in general, overshadow that of the tangential stress.

If the stress exceeds the critical stress σ_0 , the recorded spot

is expected to have the form shown in Fig. 3. Such a shape is, in fact, seen in Fig. 4. The film was first locked⁶ into the hard direction by a uniform field (as may be deduced from the Néel wall pairs) and then switched to an easy direction by a laser light pulse in coincidence with an easy direction bias field to assure rotation of the magnetization into one direction. The wall structure along the easy axis of the recorded spot supports the model of Fig. 3.

While apparent rotation of the anisotropy is a principal consequence of an applied stress to a magnetostrictive film, other magnetic changes are observed⁵ which probably

Table 1 Stress values.

r/b	reduced stress	
	σ_r/σ'	σ_θ/σ'
0	1.0	1.0
.1	.99	.97
.2	.96	.88
.3	.91	.73
.4	.84	.52
.5	.75	.25
.6	.64	0
.7	.51	
.8	.36	
.9	.19	
1.0	0	

play an important role in thermostrictive recording. Both the anisotropy field and the angular dispersion are seen to change under stress and may enhance or inhibit the switching of the magnetization depending on the direction of the applied stress.

The energy required to record by thermostriction is obtained by combining Eq. (3) with the criteria for recording, Eqs. (5) and (6),

$$E = \frac{2}{3} \frac{M_s H_k}{\lambda_s} \frac{V \rho C}{\alpha Y}, \quad (7)$$

where V is the volume of the material irradiated by the beam. This represents the critical energy needed for recording by either a laser or an electron beam. A plot of Eq. (7) (energy vs. magnetostriction) superimposed with Eq. (3) (energy vs. temperature rise) is given in Fig. 5. While an accurate determination of the beam energies used in the experiments could not be made, order-of-magnitude estimates were in agreement with the calculations. It is evident that the magnetostriction must exceed 10^{-6} in order to avoid annealing the magnetic film and destroying the uniaxial properties. A test of the correctness of our model is found in this criterion. It is indeed seen that, after recording on films of $\lambda_s = 10^{-6}$, isotropic regions are observed when the beam energy is increased above that needed to effect recording. On the basis of our model, then, films with magnetostriction of the order of 10^{-5} will be required.

Assuming a film thickness of $500 \text{ \AA}$, $\lambda_s = 10^{-5}$, and a spot density of 10^7 bits per square inch and hence 8 micron diameter spots, 10^{-10} joules of energy will be required of the beam with a 20°C temperature rise in the film. Assuming 10 per cent efficiency and a one megabit per second information rate, a beam power of 10^{-3} watts will be adequate.

Switching modes

There are three important modes of switching a uniaxial film with the application of a local stress (Fig. 6). The first of these (Fig. 6a) is a bidirectional mode; the magnetization may be switched into either easy direction by the coincident application of a stress and the appropriate easy direction bias field. The bias field is selected to approach but not exceed the wall motion threshold. With the coincident application of a local stress, the anisotropy is rotated so that, at some angle, the bias field exceeds the rotational threshold and the magnetization rotates into the opposite easy direction. With low dispersion films, this rotation might be as small as 5° . While being reasonably sensitive to beam energies, the mode is also sensitive to film nonuniformities and dispersion. In general, a low dispersion film is also one of low coercive force, which forces the use of low bias fields and decreases the sensitivity to beam energy. However, because of the anti-

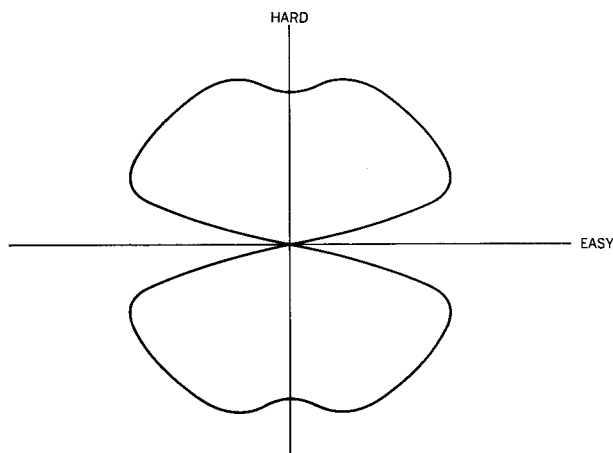
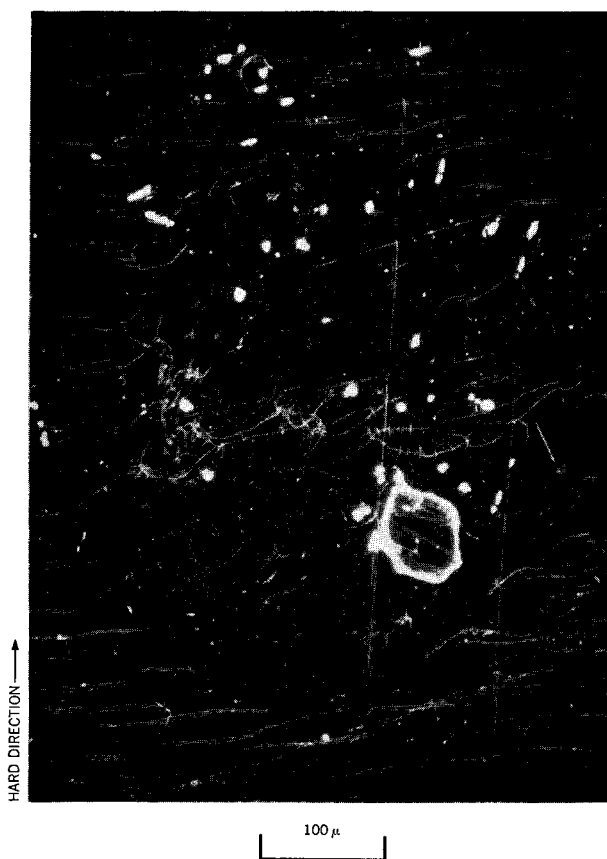


Figure 3 Recorded spot (theoretical).

Figure 4 Recorded spot (observed).



parallel storage, assuming a Kerr or Faraday optical readout, maximum polarization rotation will be experienced. Furthermore, readout may coincide with recording in that only the bit undergoing recording will be influenced by the fields. The density storage capability is not known

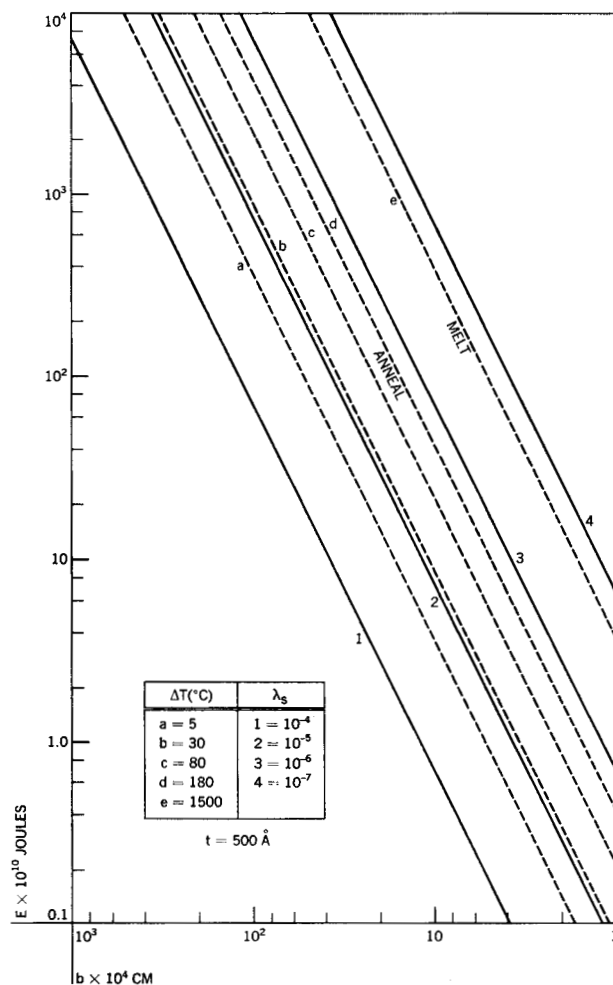
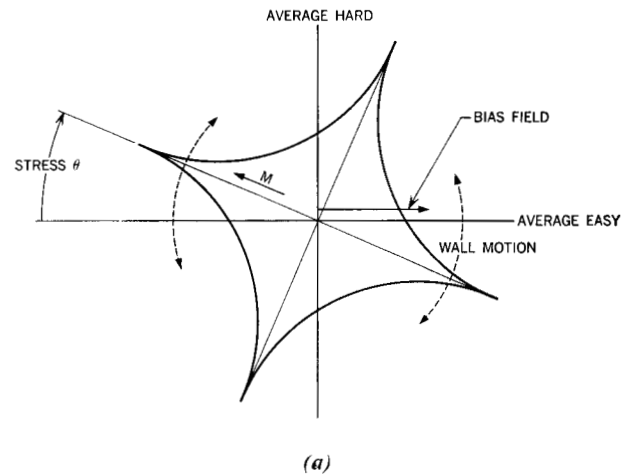


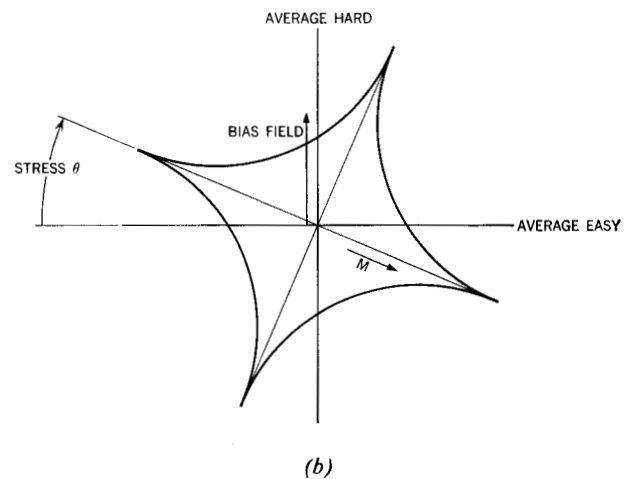
Figure 5 Beam energy vs diameter of recorded spot, for several values of magnetostriction and temperature change.

at this writing but is believed to be well in excess of 10^6 bits per square inch for very thin films.

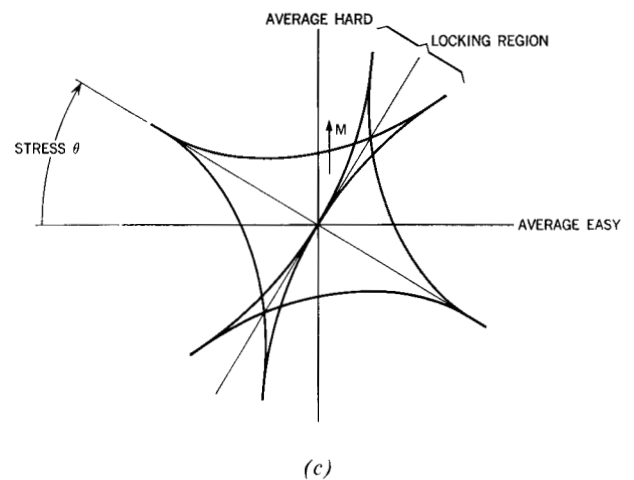
A second bidirectional storage mode (Fig. 6b) uses a hard direction bias field in coincidence with a local stress, where the storage sense is determined by the sense of the bias field. Here, the bias field is selected to approach, but not exceed, the anisotropy field. With the coincident application of a local stress the anisotropy is rotated sufficiently for the bias field to exceed the rotational threshold and for the magnetization to rotate toward the opposite easy direction state after the removal of the field. This mode is particularly sensitive to the beam energy and may require rotations as small as 2° for very low dispersion films. This mode is not particularly sensitive to the wall motion threshold or film variations (other than the property of skew, which must be held to 1° for a 1° film). The antiparallel store is desirable for optical readout, but because of the rotation into the hard direction, large blocks of information would not be accessible for readout during



(a)



(b)



(c)

Figure 6 Switching modes: (a) bidirectional, easy-direction bias; (b) bidirectional, hard-direction bias; (c) dispersion-locked

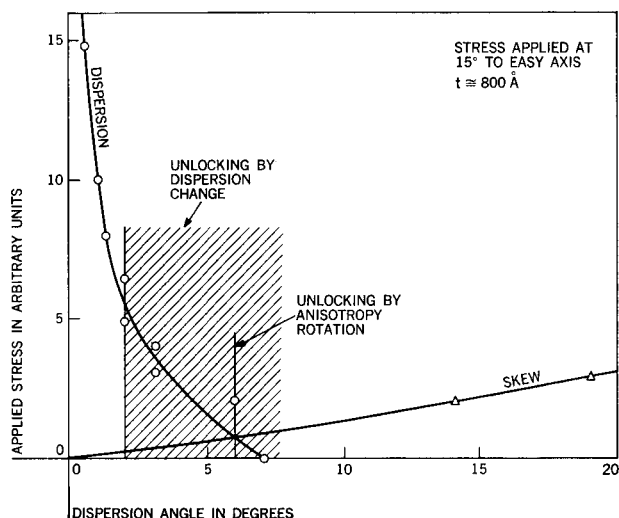


Figure 7 Applied stress vs dispersion for dispersion-locked mode.

recording anywhere in the block influenced by the bias field. Again, the storage capability is believed to be in excess of 10^6 bits per square inch.

The third storage mode (Fig. 6c) makes use of the storage capability of the hard direction⁶ found in Permalloy films whose dispersion exceeds 8° . The switching asteroids of Fig. 6c are a schematic representation of the locking region and are not meant to describe the mechanism of locking. (For further information on hard direction locking and the mechanism thereof, see References 7, 8, 9, 10). Here the switching is unidirectional. The block is first locked into a hard direction and the field removed. By the application of a local stress, the anisotropy is rotated while the magnetization remains locked into the average hard direction by the locking walls. When the locking region rotates beyond the average hard direction, the magnetization of that region rotates into an easy direction under the influence of the anisotropy forces. The role of dispersion change is particularly significant in this mode. Observations on high dispersion Permalloy films show that full locking is achieved with dispersions greater than 8° ; it diminishes to negligible remanence in the hard direction at 2° . Recording with stress in the dispersion-locked mode is demonstrated in Fig. 7, where a Permalloy film is stressed over a fulcrum along an arbitrary direction from the easy axis. We note that as the anisotropy rotates the angular dispersion is decreasing, and unlocking* occurs at the intersection of these curves. We note further that unlocking would occur even in the absence of the anisotropy rotation as the angular dispersion drops to 2° . It would seem that unlocking by anisotropy rotation will

*The authors have observed in hard direction locking that the "angular extent" of locking, measured from the hard axis, is identical to that measured as "angular dispersion" by Crowther.⁵

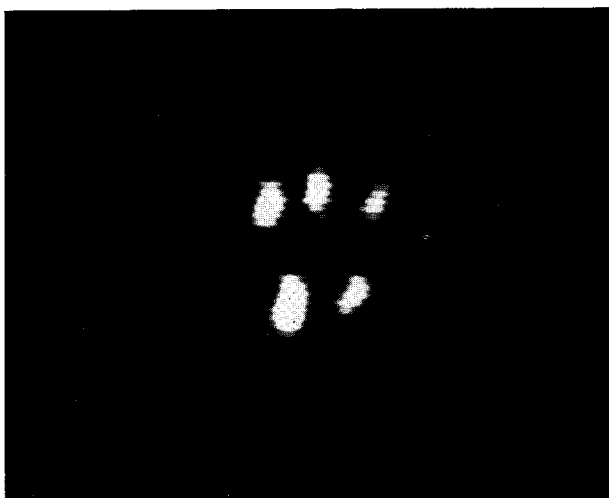
always precede that by dispersion change. To reset the information after recording, a hard direction field must be applied to the entire block of information and all the information reset into the hard direction. While it is possible to write into memory by a local stress alone, it has the disadvantage of being updated a block at a time. This mode requires 10° of rotation but is not sensitive to the film variations. The orthogonal store is less desirable from the viewpoint of readout, since the optical rotation is considerably reduced from the antiparallel store. Since the locking is dependent on the wall structure which, for typical permalloy films, has a minimum wave length of 4 microns,⁸ the storage density capability is limited to 3×10^7 bits per square inch with one Néel pair per bit. It would seem that 10^6 bits per square inch, with 6 Néel pairs per bit, is a practical limit for this mode.

Finally, as a demonstration of the possibilities of thermomagnetic recording, five 65-micron spots on 130-micron centers were recorded and displayed on a closed circuit TV system. A photograph of the display is reproduced in Fig. 8. Single 10-micron spots have also been recorded.

Summary

A new recording mechanism has been identified and described. It consists of the switching of magnetization under the influence of a stress resulting from a heat gradient introduced by a very narrow light or electron beam. The mechanism is assumed to be magnetostriction with a rotation of the anisotropy. The model presented and the criteria for recording are supported, at least in part, by experimental observations.

Figure 8 Thermomagnetically-recorded 65-micron spots, as seen using Kerr techniques.



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References

1. W. E. Glenn, "Thermoplastic Recording," *Journal of Applied Physics* **30**, 1870 (1959).
2. J. F. Dillon, J. T. Chang, V. F. Gianola, "A Magneto-Optical Variable Memory," presented at the 10th Conference on Magnetism and Magnetic Materials, Minneapolis, Minnesota, Nov. 16, 1964.
3. E. N. Mitchell, G. I. Lykken, G. D. Babcock, "Compositional and Angular Dependence of the Magnetostriction of Thin Iron-Nickel Films," *Journ. Appl. Phys.* **34**, 715 (1963).
4. C. T. Wang, *Applied Elasticity*, McGraw-Hill Publishing Co., New York, 1953.
5. T. S. Crowther, "Angular And Magnetic Dispersion of the Anisotropy in Magnetic Films," *Journ. Appl. Phys.* **34**, 580 (1963).
6. H. J. Kump, H. G. Hottenrott, B. I. Bertelsen, P. T. Chang, "The Dispersion Locked Memory Mode for Magnetic Films," *IBM Journal* **10**, 89 (1966).
7. S. Middelhoek, "Ferromagnetic Domains in the Thin Ni-Fe Films," *IBM TIC 64DI-2798* (1961).
8. H. Rother, "Magnetic Properties of Ferromagnetic Layers," *Zeitschrift der Physik*, **168**, 42, 148, 283 (1962) (3 articles).
9. H. Hoffman, "Quantitative Calculation of the Magnetic Ripple," *Journ. Appl. Phys.* **35**, 1790 (1964).
10. E. J. Torok, H. N. Oredson, A. L. Olson, "Local Regions with Biaxial Anisotropy in Thin Ferromagnetic Films," *Journ. Appl. Phys.* **35**, 3469 (1964).

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